

1 **USER AUTHENTICATION METHOD, AND STORAGE MEDIUM,**
2 **APPARATUS AND SYSTEM THEREFOR**

3 **Field of the Invention**

4 The present invention relates to a user authentication
5 method used, for example, for a computer system
6 connected to a network; a storage medium on which a user
7 authentication program is stored; a user authentication
8 apparatus; and a user authentication system. In
9 particular, the present invention pertains to a user
10 authentication method, for authenticating relations
11 existing between a prover computer, equipped with a
12 public key, and a plurality of verifier computers; a
13 storage medium on which such a user authentication
14 program is stored; and a user authentication apparatus
15 and an authentication system therefor.

16 **Background Art**

17 On a network, users are often required to participate in
18 some sort of authentication process to identify
19 themselves. An authentication process in this case
20 refers to a process whereby a prover, by following the
21 rules of a specific protocol, proves his or her identity
22 to a verifier, a requisite electronic commerce
23 technique. When, for example, a user desires to prove

1 his or her identity to a server, the user functions as a
2 prover and the server functions as a verifier. Whereas
3 when a server desires to prove its identity to a user,
4 the server functions as a prover and the user functions
5 as a verifier. Such authentication techniques are not
6 limited in their application to intercourse between
7 users and servers, but are widely employed as mutual
8 identification methods by arbitrarily paired computers.
9 Recently, the user authentication processes that are
10 employed are based on public key encryption: a prover
11 has both a public key and a secret key, and when the
12 prover desires to prove his or her identity, he or she
13 employs a specific protocol to notify a verifier that he
14 or she has a secret key that corresponds to the public
15 key.

16 The Schnorr method is a well known, representative user
17 authentication technique ("Efficient Signature
18 Generation by Smart Cards", C.P. Schnorr, Journal of
19 Cryptology, Vol. 4, No. 3, pp.161-174, 1991). According
20 to this technique, a prover proves to a verifier that he
21 or she holds a secret key corresponding to a public key.

22 As one conventional example, a summary of Schnorr's user
23 authentication method will now be given while referring
24 to Fig. 3. System parameters used by this method are
25 prime numbers p and q ($q|p-1$) and the element $g \in \mathbb{Z}_p$ of
26 the order q . The public key of the prover is v ($v = g^s$
27 $\text{mod } p$), and the secret key of the prover is $s \in \mathbb{Z}_q$. In

1 the following explanation, assume that the prover and
2 the verifier obtain in advance the prime numbers p and q
3 and the element g , which are system parameters, and that
4 the verifier obtains in advance the public key v of the
5 prover.

6 According to this method, the verifier and the prover
7 exchange data in the following manner.

8 Step 1: The prover generates a random number $a \in \mathbb{Z}_q$,
9 calculates $A = g^a \bmod p$, and transmits it to the
10 verifier.

11 Step 2: The verifier generates a random number b ($b \in$
12 \mathbb{Z}_q), and transmits it to the prover.

13 Step 3: The prover calculates $c = a + bs \bmod q$, and
14 transmits it to the verifier.

15 Step 4: The verifier determines whether $A = V^{bg^c} \bmod p$ is
16 established. If this equation is established, the
17 verifier ascertains that the identity of the prover is
18 correct. If this equation is not established, the
19 verifier ascertains that the identity of the prover is
20 incorrect, and rejects the communication.

21 The Schnorr method is the most efficient of all the
22 methods based on the discrete logarithm program, and
23 only three communications are required. However, the
24 safety of the communications is not guaranteed. That
25 is, in the process of following the procedures defined
26 in the protocol and communicating across the network,
27 the secret key s of the prover may be revealed.

1 Therefore, the safety of such a data exchange between
2 prover and verifier should be evaluated, i.e., the user
3 authentication process (the exchange of messages, etc.).

4 For this evaluation, i.e., of the safety of the user
5 authentication process, a zero-knowledge technique is
6 well known ("The Knowledge Complexity of Interactive
7 Proofs", S. Goldwasser, S. Micali, and C. Rackoff,
8 Proceedings of 17th Symposium on Theory of Computing,
9 pp. 291-304, 1985). In this instance, the zero
10 knowledge property represents that no information
11 concerning the secret key of the prover is revealed, and
12 thus, when the zero knowledge property is achieved, the
13 safety of the user authentication method is guaranteed.

14 The zero knowledge property can be achieved by a partial
15 correction to the Schnorr authentication method ("How to
16 prove yourself: practical solution to identification and
17 signature problems", A. Fiat and A. Shamir, Proceedings
18 of Crypto' 86, 1980). Specifically, when the Schnorr
19 authentication method is corrected so that the verifier
20 generates a random number $b \in \{0, 1\}$ and so that the
21 procedures in the protocol are sequentially performed O
22 $(\log q)$ times, the zero knowledge property is achieved.
23 That is, when the subsequent protocol procedures are
24 performed $O(\log q)$ times, and if the verifier accepts
25 the identity of the prover in all the performances of
26 the protocol procedures, the identity of the prover is
27 verified.

28 Protocol]

1 Step 1: The prover generates a random number $a \in \mathbb{Z}_q$,
2 calculates $A = g^a \bmod p$ and transmits the random number A
3 to the verifier.

4 Step 2: The verifier generates a random number $b \in \{0,$
5 $1\}$, and transmits the random number b to the prover.

6 Step 3: The prover calculates $c = a + b s \bmod q$, and
7 transmits the result c to the verifier.

8 Step 4: The verifier determines whether $A = v^b g^c \bmod p$
9 has been established. When the equation has been
10 established, the verifier concludes that the identity of
11 the prover is correct. If the equation is not
12 established, the verifier concludes that the identity of
13 the prover is incorrect, and rejects the communication.

14 As described above, although the number of
15 communications is increased to $O(\log q)$, the zero
16 knowledge property is achieved. Besides the Schnorr
17 method, many other user authentication methods have been
18 proposed that achieve the zero knowledge property.

19 Problems to be Solved by the Invention]

20 However, to achieve the zero knowledge property for the
21 conventional user authentication, it is proposed that
22 one prover correspond to one verifier, and that the zero
23 knowledge property will be achieved only when the prover
24 and the verifier complete the performance of the
25 protocol procedures using one-to-one correspondence (see
26 Fig. 4). That is, when the prover must perform the
27 protocol with multiple verifiers, there is no guarantee
28 that the zero knowledge property will be achieved

1 ("Concurrent Zero-Knowledge", C. Dwork, M. Naor and A.
2 Sahai, Proc. Of 30th STOC, 1998).

3 For example, on an asynchronous network, such as the
4 Internet, multiple computers simultaneously communicate
5 with each other, and a prover may also be required to
6 simultaneously perform the protocol procedures with
7 multiple verifiers. On the WWW (the World Wide Web), an
8 HTTP (Hyper Text Transfer Protocol: the protocol used by
9 WWW servers and WWW browsers or Web browsers to exchange
10 such data as files) server is requested to verify its
11 identity through simultaneous communication exchanges
12 with multiple connected clients (see Fig. 5)

13 Summary of the Invention

14 To resolve the above shortcoming, it is one object of
15 the present invention to provide a user authentication
16 method whereby, even when multiple verifiers are in
17 simultaneous communication with a prover, a user can be
18 safely authenticated while at the same time the zero
19 knowledge property is achieved, as well as a storage
20 medium on which such a user authentication program is
21 stored, and a user authentication apparatus and a user
22 authentication system therefor.

23 To achieve the above object, according to one aspect of
24 the present invention, a user authentication method,
25 whereby a one-way function F , which should satisfy $v =$

1 $F(g, -s)$, is determined by employing an integer g that
2 is defined in advance for a relation between a public
3 key v and a secret key s of a prover computer, and
4 whereby a relation is verified between the prover
5 computer and each of multiple verifier computers,
6 comprises the steps of: the prover computer generating a
7 random number a , obtaining a cryptogram $A =$ the function
8 $F(g, a)$, and transmitting the cryptogram A to the
9 verifier computers; the verifier computers generating a
10 random number b , obtaining a cryptogram $B =$ the function
11 $F(g, b)$ and a cryptogram $X =$ the function $F(A, b)$, and
12 transmitting the cryptograms B and X to the prover
13 computer; the prover computer determining whether a
14 relation of the cryptogram $X =$ the function $F(B, a)$ has
15 been established and generating a random number c when
16 the relation has been established, obtaining a
17 cryptogram $C =$ the function $F(g, c)$ and a cryptogram $Y =$
18 the function $F(B, c)$, or a cryptogram $C =$ the function
19 $F(A, c)$, a cryptogram $Y =$ the function $F(X, c)$ and a
20 cryptogram $Z =$ a function $H(a, Y, s)$, and transmitting
21 the cryptograms C and Y or the cryptograms C, Y and Z to
22 the verifier computers; and the verifier computers, when
23 the cryptogram $Y =$ the function $F(C, b)$ and the
24 cryptogram $A =$ a function $J(v, Y, g, Z)$ are established,
25 determining that the relation between the prover
26 computer and the verifier computer is correct.

27 The public key v is obtained by employing prime numbers
28 p and q that satisfy $(q|p - 1)$; and by defining an
29 element of the order q as the integer g .

1 By using the public key v and the secret key s , the
2 function F acquires a relation $v = F(g, -s) = g^{-s} \bmod p$.

3 When a relation $X = B^a \bmod p$ is established, the prover
4 computer generates the random number c .

5 The function H has a relation $H(a, Y, s) = a + Ys \bmod q$.

6 The function J has a relation $J(v, Y, g, Z) = v^Y g^Z \bmod p$.

7 According to another aspect of the invention, a storage
8 medium is provided on which a user authentication
9 program, which is to be read by a prover computer, is
10 stored whereby a one-way function F , which should
11 satisfy $v = F(g, -s)$, is determined by employing an
12 integer g , which is defined in advance for the relation
13 between a public key v and a secret key s of the prover
14 computer, and whereby a relation is verified between the
15 prover computer and each of multiple verifier computers,
16 the user authentication program permitting the prover
17 computer to perform: a process for generating a random
18 number a and for obtaining a cryptogram $A =$ the function
19 $F(g, a)$, and for transmitting the cryptogram A to the
20 verifier computers; a process for receiving cryptograms
21 B and X from the verifier computer, and for employing
22 the cryptograms to determine whether a relation a
23 cryptogram $X =$ the function $F(B, a)$ has been
24 established; a process for generating a random number c
25 when the relation has been established; and a process
26 for obtaining a cryptogram $C =$ the function $F(g, c)$ and
27 a cryptogram $Y =$ the function $F(B, c)$, or a cryptogram C

1 = the function $F(A, c)$, a cryptogram Y = the function
2 $F(X, c)$ and a cryptogram Z = the function $H(a, Y, s)$;
3 and a process for transmitting the cryptograms C and Y ,
4 or C, Y and Z , to the verifier computers.

5 According to an additional aspect of the present
6 invention, a storage medium is provided on which is
7 stored a user authentication program, which is to be
8 read by a prover computer, whereby a one-way function F ,
9 which should satisfy $v = F(g, -s)$, is determined by
10 employing an integer g , which is defined in advance for
11 the relation between a public key v and a secret key s
12 of the prover computer, and whereby a relation is
13 verified between the prover computer and each of
14 multiple verifier computers, the user authentication
15 program permitting the verifier computers to perform: a
16 process for receiving a cryptogram A from the prover
17 computer and for generating a random number b ; a process
18 for obtaining a cryptogram B = the function $F(g, b)$ and
19 a cryptogram X = the function $F(A, b)$, using the random
20 number b and the cryptogram that is received, and for
21 transmitting the cryptograms B and X to the prover
22 computer; a process for receiving, from the prover
23 computer, a cryptogram C = the function $F(g, c)$ and a
24 cryptogram Y = the function $F(B, c)$, or a cryptogram C =
25 the function $F(A, c)$, a cryptogram Y = the function $F(X,$
26 $c)$ and a cryptogram Z = the function $H(a, Y, s)$; and a
27 process, based on the cryptograms C and Y or C, Y and Z
28 that are received, for verifying a relation between the
29 verifier computer and the prover computer when two

1 relations of the cryptogram $Y = \text{the function } F(C, b)$ and
2 the cryptogram $A = \text{the function } J(v, Y, g, Z)$ are
3 established at the same time.

4 According to a further aspect of the present invention,
5 a user authentication apparatus is provided for a prover
6 computer, wherein a one-way function F , which should
7 satisfy $v = F(g, -s)$, is determined by employing an
8 integer g , which is defined in advance, for a relation
9 between a public key v and a secret key s of the prover
10 computer, and wherein a relation is verified between the
11 prover computer and each of multiple verifier computers,
12 the user authentication apparatus comprising:
13 transmission means, for generating a random number a and
14 obtaining a cryptogram $A = \text{the function } F(g, a)$, and for
15 transmitting the obtained cryptogram A to the verifier
16 computers; reception means, for receiving cryptograms B
17 and X from the verifier computers; verification means,
18 for employing the cryptograms B and X to determine
19 whether a relation of the cryptogram $X = \text{the function}$
20 $F(B, a)$ has been established; cryptogram computation
21 means, for generating a random number c when it has been
22 ascertained that the relation has been established, and
23 for obtaining a cryptogram $C = \text{the function } F(g, c)$ and
24 a cryptogram $Y = \text{the function } F(B, c)$, or a cryptogram C
25 $= \text{the function } F(A, c)$, a cryptogram $Y = \text{the function}$
26 $F(X, c)$ and a cryptogram $Z = \text{the function } H(a, Y, s)$;
27 and cryptogram transmission means, for transmitting the
28 cryptograms C and Y or C, Y and Z to the verifier
29 computers.

1 According to a still further aspect of the prevent
2 invention, a user authentication apparatus is provided
3 for a prover computer wherein a one-way function F ,
4 which should satisfy $v = F(g, -s)$, is determined by
5 employing an integer g , which is defined in advance, for
6 the relation between a public key v and a secret key s
7 of a prover computer, and wherein a relation is verified
8 between the prover computer and each of multiple
9 verifier computers, the user authentication apparatus
10 comprising: reception means, for receiving a cryptogram
11 A from the prover computer; transmission means, for
12 generating a random number b , and for employing the
13 random number b and the cryptogram A that is received to
14 obtain a cryptogram $B = \text{the function } F(g, b)$ and a
15 cryptogram $X = \text{the function } F(A, b)$, and for
16 transmitting the cryptograms B and X to the prover
17 computer; cryptogram reception means, for receiving from
18 the prover computer a cryptogram $C = \text{the function } F(g,$
19 $c)$ and a cryptogram $Y = \text{the function } F(B, c)$ or a
20 cryptogram $C = \text{the function } F(A, c)$, a cryptogram $Y =$
21 $\text{the function } F(X, c)$, and a cryptogram $Z = \text{the function}$
22 $H(a, Y, s)$; and verification means, for performing a
23 procedure, based on the cryptograms C , Y and Z that are
24 received, for verifying a relation between the verifier
25 computers and the prover computer when two relations of
26 the cryptogram $Y = \text{the function } F(C, b)$ and the
27 cryptogram $A = \text{the function } J(v, Y, g, Z)$ are
28 established at the same time.

1 According to yet one more aspect of the present
2 invention, a user authentication system comprises: the
3 above described user authentication apparatus for the
4 prover computer; and a plurality of the above described
5 user authentication apparatuses for the verifier
6 computers.

7 According to yet another aspect of the present
8 invention, a user authentication system, wherein a
9 one-way function F , which should satisfy $v = F(g, -s)$,
10 is determined by employing an integer g , which is
11 defined in advance, for the relation between a public
12 key v and a secret key s of a prover computer, and
13 wherein a relation is verified between the prover
14 computer and each of multiple verifier computers,
15 comprises: transmission means, for the prover computer,
16 for generating a random number a and obtaining a
17 cryptogram $A = \text{the function } F(g, a)$, and for
18 transmitting the obtained cryptogram A to the verifier
19 computers; reception means for the verifier computers,
20 for receiving the cryptogram A from the prover computer;
21 transmission means for the verifier computers, for
22 generating a random number b with which the cryptogram A
23 is employed to obtain a cryptogram $B = \text{the function } F(g,$
24 $b)$ and a cryptogram $X = \text{the function } F(A, b)$, and for
25 transmitting the cryptograms B and X to the prover
26 computer; reception means for the prover computer, for
27 receiving the cryptograms B and X from the verifier
28 computers; verification means for the prover computer,
29 for employing the cryptograms B and X to determine

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1 whether a relation of the cryptogram X = the function
2 $F(B, a)$ has been established; cryptogram computation
3 means for the prover computer, for generating a random
4 number c when it is ascertained that the relation has
5 been established, and for obtaining the cryptogram C =
6 the function $F(g, c)$ and the cryptogram Y = the function
7 $F(B, c)$, or the cryptogram C = the function $F(A, c)$ and
8 the cryptogram Y = the function $F(X, c)$, and a
9 cryptogram Z = the function $H(a, Y, s)$; and cryptogram
10 transmission means for the prover computer, for
11 transmitting the cryptograms C, Y and Z to the verifier
12 computers; cryptogram reception means, for the verifier
13 computers, for receiving the cryptograms C, Y and Z from
14 the prover computer; and verification means for the
15 verifier computers, for employing the cryptograms C, Y
16 and Z that are received to verify a relation between the
17 verifier computers and the prover computer when two
18 relations of the cryptogram Y = the function $F(C, b)$ and
19 the cryptogram A = the function $J(v, Y, g, Z)$ are
20 established at the same time.

21 Preferred Embodiment

22 The preferred embodiment of the present invention will
23 now be described while referring to the accompanying
24 drawings. In this embodiment, the invention is applied
25 for a case wherein a public key v and a secret key s are
26 used for user authentication on a network.

27 The present invention relates to user authentication for

1 an asynchronous network, such as the Internet. In the
2 asynchronous network, multiple verifiers may request a
3 prover to execute a protocol for user authentication.
4 That is, in this embodiment, there are multiple
5 verifiers for one prover.

6 In this embodiment, the following one-way function F is
7 employed as an encryption function. Assume that the
8 one-way function F is a two-input and one-output
9 function, and that two calculations, addition (+) and
10 multiplication (*) are defined by the range and a second
11 variable range of a function.

12 Further, the function F satisfies the following two
13 properties.

14 That is, for arbitrary an a and b, the following
15 relations must be established:

16
$$(1) F(g, a+b) = F(g, a) * F(g, b)$$

17
$$(2) \text{ if } A = F(g, a), F(g, a*b) = F(A, b).$$

18 Another encryption function H, which is a three-input
19 and one-output function, is represented as follows.

20
$$H(a, Y, s) = a + Y*s$$

21 wherein the addition and multiplication are the ones
22 defined in the second variable range of the function F.
23 Furthermore, an additional encryption function J, which
24 is a four-input and one-output function, is represented
25 as follows using the function F.

26
$$J(v, Y, g, Z) = F(v, Y) * F(g, Z).$$

27 The one-way function based on the discrete logarithm can
28 be a specific example for the function F. As a typical

1 example, when a relation $q|p-1$ is established for prime
2 numbers p and q and when $g \in \mathbb{Z}_p$ is the element of the
3 order q ,
4 $F(g, a) = g^a \text{ mod } p$.

5 A system for which the present invention can be applied
6 is shown in Fig. 2. A prover computer 10 and a verifier
7 computer 40, which include at the least a CPU, and
8 additional verifier computers 60 having the same
9 configuration as the verifier computer 40 are connected
10 to a network 32. As is shown in Fig. 2, in this
11 embodiment, a one-to-multiple connection is established
12 between the prover computer and the verifier computers.

13 The prover computer 10 includes an input device 12, for
14 entering system parameters, is connected to a random
15 number generator 14, for generating a random number a in
16 accordance with the input, and a memory 16. The random
17 number generator 14 is connected to the memory 16 and a
18 cryptogram calculator 18, for obtaining a cryptogram A
19 based on the random number a . The cryptogram calculator
20 18 is connected to a communication interface
21 (hereinafter referred to as a communication I/F) 30,
22 which in turn is connected to the network 32, to
23 facilitate communications with other apparatuses via the
24 network 32. A verification unit 20 is connected both to
25 the communication I/F 30 and to the memory 16. A random
26 number generator 22, for generating a random number c in
27 accordance with the input, and a halting unit 24, for
28 employing an input signal to halt a protocol that will

1 be described later, are connected to the verification
2 unit 20. The random number generator 22 is connected to
3 a cryptogram calculator 26, for obtaining cryptograms C
4 and Y, based on the random number c. The cryptogram
5 calculator 26 is connected to a cryptogram calculator
6 28, for obtaining a cryptogram Z, based on the
7 cryptograms C and Y. And the cryptogram calculators 26
8 and 28 are connected both to the communication I/F 30
9 and to the memory 16.

10 The verifier computer 40 includes an input device 42,
11 for entering system parameters, that is connected to a
12 random number generator 44, for generating a random
13 number b in accordance with the input, and a memory 46.
14 The random number generator 44 is connected to the
15 memory 46 and a cryptogram calculator 48, for obtaining
16 cryptograms B and X based on the random number b. The
17 cryptogram calculator 48 is connected to a communication
18 I/F 56, which is connected to the network 32 to
19 facilitate communications with other apparatuses via the
20 network 32. A verification unit 50 is connected both to
21 the communication I/F 56 and to the memory 46. And an
22 acceptance unit 52 and a rejection unit 54 are connected
23 to the output side of the verification unit 50.

24 Since the verifier computer 60 has the same
25 configuration as the verifier computer 40, no detailed
26 explanation for it will be given. In the following
27 description, wherein the verifier computer 40 is used as
28 a typical configuration, the names of its individual

1 sections are employed.

2 The protocol for this embodiment will now be described.
3 It should be noted that the system parameter is a
4 function F_g , the public key of a prover is $v = F(g, -s)$,
5 and the secret key of the prover is s .

6 Protocol

7 Step 1:

8 A prover generates the random number a using the random
9 number generator 14, obtains a cryptogram $A = F(g, a)$
10 using the cryptogram calculator 18, and transmits the
11 cryptogram A to verifiers via the communication I/F 30.
12 Step 1 corresponds to a process $Ps1$, which is performed
13 by the prover computer 10 in Fig. 1, and communication
14 $T1$, which is transmitted as a result of the process $Ps1$.

15 Step 2:

16 The verifier generates the random number b using the
17 random number generator 44, and employs the received
18 cryptogram A to obtain a cryptogram $B = F(g, b)$ and a
19 cryptogram $X = F(A, b)$. The verifier then transmits the
20 obtained cryptograms B and X to the prover via the
21 communication I/F 30.

22 Step 2 corresponds to a process $Qs1$, which is performed
23 after the verifier computer 40 in Fig. 1 has received
24 the data accompanying the communication $T1$, and to
25 communication $T2$, which is transmitted as a result of
26 the process $Qs1$.

1 Step 3:
2 Based on the received cryptograms B and X, the prover
3 employs the verification unit 20 to determine whether X
4 $= F(B, a)$ has been established for the verifier. If $X =$
5 $F(B, a)$ has not been established for the verifier, the
6 prover ascertains that the verifier performed an illegal
7 activity, and halts the performance of the protocol
8 procedures using the halting unit 24. If, however, $X =$
9 $F(B, a)$ has been established for the verifier, the
10 prover generates the random number c and obtains $C =$
11 $F(g, c)$ and $Y = F(B, c)$, or alternately, obtains $C =$
12 $F(A, c)$ and $Y = F(X, c)$. Afterwards, $Z = H(a, Y, s)$,
13 i.e., $Z = a + Y*s$ is calculated, and then the obtained
14 cryptograms C, Y and Z are transmitted to the verifier.
15 Step 3 corresponds to a process Ps2, which is performed
16 after the prover computer 10 in Fig. 1 has received the
17 data accompanying the communication T2, and to
18 communication T3, which is transmitted because the
19 relation $X = F(B, a)$ was verified by the verification
20 unit 20 during the process Ps2.

21 Step 4:
22 Based on the received cryptograms C, Y and Z , the
23 verifiers uses the verification unit 50 to determine
24 whether $Y = F(c, b)$ and $A = J(v, Y, g, Z)$, i.e., $A =$
25 $F(v, Y)*F(g, Z)$, have been established. If the two
26 relations have been established, the verifier accepts
27 the identity of the prover (the acceptance unit 52 is
28 activated). If, however, the two relations have not

1 been established, the verifier rejects the identity of
2 the prover (the rejection unit 54 is activated).
3 Step 4 corresponds to a process Qs2 performed after the
4 verifier computer 40 in Fig. 1 has received the data
5 accompanying the communication T3.

6 The above protocol can be stored as a program, for use
7 by the prover and the verifiers, on a storage medium,
8 such as a floppy disk. In this case, only a detachable
9 floppy disk unit (FDU) need be connected to the
10 individual computers to enable the program to be read
11 from the floppy disk and executed.

12 A processing program may be stored (installed) in a RAM,
13 or at another storage area (e.g., on a hard disk) in the
14 computer, and executed, or it may be stored in a ROM in
15 advance. A storage medium, a disk such as a CD-ROM, an
16 MD, an MO or a DVD, or a magnetic tape such as a DAT,
17 may also be used, but when one of these media is
18 employed, a corresponding device, such as a CD-ROM
19 drive, an MD drive, an MO drive, a DVD drive or a DAT
20 drive must be provided.

21 Specific Example:

22 A specific example of user authentication for which the
23 above described protocol is employed will now be
24 described. In the following example, when prime numbers
25 p and q ($q|p - 1$) and the element g of the order q are
26 employed as system parameters, $v = F(g, -s) = g^{-s} \bmod p$
27 is employed as the function F . That is, the same key

1 configuration as that provided by the Schnorr method can
2 be employed. Further, the function H is defined as $H(a,$
3 $Y, s) = a + Y s \bmod q$, and the function J is defined as
4 $J(v, Y, g, Z) = v^Y g^Z \bmod p$.

5 Key configuration]

6 System parameters: prime numbers p and q ($q|p - 1$) and
7 the element g of the order q

8 Public key of a prover: $v = g^{-s} \bmod p$

9 Secret key of a prover: $s \in \mathbb{Z}_q$

10 Protocol]

11 Step 1: The prover generates the random number a,
12 acquires a cryptogram A and transmits the cryptogram A
13 to the verifier.

14 $a \in \mathbb{Z}_q$... (1)

15 $A = g^a \bmod p$... (2)

16 That is, at the prover computer 10, the random number
17 generator 14 employs the system parameter q to generate
18 the random number a, in accordance with expression (1),
19 and the cryptogram calculator 18 employs the random
20 number a and the system parameters p and q to obtain the
21 cryptogram A, in accordance with expression (2). The
22 obtained cryptogram A is then output through the
23 communication I/F 30, and is transmitted, via the
24 network 32, to the verifier computer 40.

25 Step 2: The verifier generates the random number b,
26 obtains cryptograms B and X, and transmits the
27 cryptograms B and X to the prover.

1 $b \in \mathbb{Z}_q$... (3)

2 $B = g^b \text{ mod } p$... (4)

3 $X = A^b \text{ mod } p$... (5)

4 That is, at the verifier computer 40, the cryptogram
 5 calculator 48 receives the cryptogram A, generated by
 6 the prover computer 10, via the communication I/F 56.
 7 At this time, the random number generator 44 of the
 8 verifier computer 40 employs the system parameter q to
 9 generate the random number b, in accordance with
 10 expression (3). The cryptogram calculator 48 then
 11 employs the random number b and the received cryptogram
 12 A to obtain the cryptograms B and X, in accordance with
 13 expressions (4) and (5), and the obtained cryptograms B
 14 and X are output through the communication I/F 56 and
 15 are transmitted, via the network 32, to the prover
 16 computer 10.

17 Step 3: The prover employs the cryptograms B and X to
 18 determine whether the following expression (6) has been
 19 established. If expression (6) has not been
 20 established, the prover assumes that the verifier
 21 performed an illegal activity and halts the protocol.
 22 If, however, expression (6) has been established, the
 23 prover generates the random number c and obtains
 24 cryptograms C and Y. Thereafter, a cryptogram Z is
 25 acquired, and the cryptograms C, Y and Z are transmitted
 26 to the verifier.

27 $X = B^a \text{ mod } p$... (6)

28 $c \in \mathbb{Z}_q$... (7)

- 1 $C = g^c \text{ mod } p \quad \dots(8)$
- 2 $Y = B^c \text{ mod } p \quad \dots(9)$
- 3 or $C = A^c \text{ mod } p \quad \dots(10)$
- 4 $Y = X^c \text{ mod } p \quad \dots(11)$
- 5 $Z = a + Y s \text{ mod } q \quad \dots(12)$

6 Specifically, at the prover computer 10 the verification
7 unit 20 receives the cryptograms B and X from the
8 verifier computer 40 via the communication I/F 30, and
9 employs the cryptograms B and X that are received and
10 the system parameters stored in the memory 16 to examine
11 the cryptograms B and X, in accordance with expression
12 (6).
13 If expression (6) has not been established, the
14 verification unit 20 transmits a signal to the halting
15 unit 24 to halt the performance of the protocol
16 procedures. When expression (6) has been established,
17 however, the verification unit 20 outputs a signal to
18 the random number generator 22 to generate the random
19 number c at the random number generator 44 based on the
20 system parameter q, following which the random number c
21 is transmitted to the cryptogram calculator 26, which
22 employs the random number c, the received cryptogram B
23 and the system parameters p and g to obtain cryptograms
24 C and Y, in accordance with expressions (8) and (9), or
25 (10) and (11). Then, in accordance with expression
26 (12), the cryptogram calculator 26 obtains a cryptogram
27 Z using the obtained cryptogram Y, the random number a,
28 the secret key s and the system parameter q, and
29 thereafter, the cryptograms C, Y and Z are output
30 through the communication I/F 30, and are transmitted,

1 via the network 32, to the verifier computer 40.

2 Step 4: The verifier determines whether the following
3 expressions (13) and (14) have been established. If the
4 two expressions have been established, the verifier
5 accepts the identity of the prover. Otherwise, the
6 verifier rejects the identity of the prover.

7
$$Y = C^b \text{ mod } p \quad \dots(13)$$

8
$$A = v^Y g^Z \text{ mod } p \quad \dots(14)$$

9 Specifically, in the verifier computer 40, the
10 verification unit 50 receives the cryptograms C, Y and Z
11 from the prover computer 10 via the communication I/F
12 56. Then, in accordance with expressions (13) and (14),
13 the verification unit 50 examines the cryptograms C, Y
14 and Z using the system parameters stored in the memory
15 46.

16 When expressions (13) and (14) have not been
17 established, the verification unit 50 activates the
18 rejection unit 54 to reject the identity of the prover.
19 When, however, the expressions (13) and (14) have been
20 established, the verification unit 50 activates the
21 acceptance unit 52 to accept the identity of the prover.

22 In this embodiment, user authentication can be completed
23 through the exchange of only three communications by the
24 prover and the verifier, and the quantity of the
25 communications contributes to the prime numbers p and q.
26 According to this embodiment, the number of
27 communications is $|p|$, using the cryptogram A
28 accompanying communication T1, $2|p|$, using the

1 cryptograms B and X accompanying communication T2, and
2 $2|p|$ and $|q|$, using the cryptograms C, Y and Z
3 accompanying communication T3 (see Fig. 1). Therefore,
4 a total of only $5|p| + |q|$ communications is required.
5 Further, as is apparent from the above expressions, this
6 contributes greatly to the reduction of the load imposed
7 by the calculation of powers. Since only six such
8 calculations are required, an efficient protocol is
9 provided.

10 In this example, communication between one prover and a
11 single verifier (one verifier) has been employed.
12 However, on an asynchronous network, such as the
13 Internet, the authentication of the identity of a prover
14 must be accomplished by multiple verifiers. In this
15 embodiment, when individual verifiers are in any of the
16 communication states corresponding to communication T1
17 to communication T3 (see Fig. 1), secrecy can be
18 maintained; a secret key will not be compromised even
19 when the cryptograms A, B, C, X, Y and Z that are
20 transmitted are trapped en route and analyzed. This
21 will be explained later in detail. Therefore, even when
22 multiple verifiers must simultaneously or sequentially
23 be permitted to examine the identity of a prover, the
24 user authentication process can be precisely performed
25 for each of the multiple verifiers. Thus, when multiple
26 verifiers are permitted to examine the identity of a
27 prover via an asynchronous network, such as the
28 Internet, the user authentication process can be
29 performed safely.

1 In the above example, the power calculation for Z_p is
2 employed as a specific one-way function F , and is a
3 so-called one-way function based on a discrete
4 logarithm. However, the present invention is not
5 limited to this problem; while N is a composite number,
6 the discrete logarithm for Z_N may be employed, or the
7 discrete logarithm for an elliptic curve may be
8 employed.

9 Validity of protocol]

10 The validity of the protocol for this embodiment will
11 now be described. Specifically, an explanation will be
12 given based on the above Specific example wherein it is
13 shown that the zero knowledge property is achieved, even
14 when the protocol for this embodiment is applied for an
15 asynchronous network. Whereas it is well known that the
16 zero knowledge property is not achieved when the
17 protocol mentioned in the description of the background
18 art ("Concurrent Zero-Knowledge", C. Dwork, M. Naor and
19 A. Shai, Proc. Of 30th STOC, 1998) is applied for an
20 asynchronous network.

21 On an asynchronous network, a plurality of illegal
22 verifiers (V_1, V_2, \dots and V_n) may enter into a
23 conspiracy with each other to communicate with a prover
24 P . Therefore, it is not sufficient to consider the
25 achievement of the zero knowledge property for
26 communications between a prover P and a single verifier
27 V . In other words, the zero knowledge property for
28 communications between a prover P and multiple verifiers

1 V1 to Vn must be taken into account.

2 In the authentication process in this embodiment, it is
3 proved that the information that can be obtained through
4 communication, in accordance with the proposed protocol,
5 with the prover P by multiple illegal verifiers V1 to
6 Vn, who have entered into a conspiracy with each other,
7 can be obtained without the communication with the
8 prover P. Specifically, it is proved for arbitrary
9 illegal verifiers V1 to Vn, there is an algorithm S
10 (simulator) such that the probability distribution of
11 the output of S matches the one of the contents of the
12 actual communications exchanged by the prover P and each
13 verifier V1 to Vn. In this embodiment, this proof is
14 represented as "the algorithm S simulates the contents
15 of the actual communication between the prover P and
16 each verifier V1 to Vn".

17 Conspiracy of verifiers]

18 It may be assumed that, without losing generality, the
19 illegal verifiers V1 to Vn in a conspiracy communicate
20 with the prover P in the following manner. The
21 verifiers V1 to Vn are sorted into groups G1, G2, ...
22 and Gm ($m \leq n$). Intuitively, it is assumed that a
23 verifier who belongs to the group G_i communicates with
24 the prover P based on information obtained by a verifier
25 who belongs to the group G_{i-1}.

26 Generalized conspiracy protocol]

27 The input data are employed as the public key for the

1 prover P and as the system parameters (p, q, g, v) .

2 Step 1: The prover P calculates cryptograms $A_1 = g^{a_1}$, A_2
3 $= g^{a_2}$, ... and $A_n = g^{a_n} \bmod p$, and transmits the obtained
4 cryptograms A_1, A_2, \dots and A_n to the respective
5 verifiers V_1, V_2, \dots and V_n .

6 The information obtained by the verifiers V_1 to V_n is
7 $VIEW_0 = \{(p, q, g, v), (A_1, A_2, \dots, A_n)\}$.

8 Step 2-1-P: All the verifiers V_i who belong to the group
9 G_1 employ the received cryptograms A_1 to A_n to generate
10 a random number $b_i \in \mathbb{Z}_q$, and obtain cryptograms $B_i (= g^{b_i}$
11 $\bmod p)$ and $X_i (= A_i^{b_i} \bmod p)$. The verifiers V_i then
12 transmit the obtained cryptograms B_i and X_i to the
13 prover P.

14 Step 2-1-V: The prover P examines each i that satisfies
15 $V_i \in G_1$ to determine whether the authentication
16 expression $(X_i = B_i^{a_i} \bmod p)$ has been established.
17 If the authentication expression has been established,
18 the prover P transmits the cryptograms C_i, Y_i and Z_i to
19 the verifiers V_i .
20 At this time, the information obtained by the verifiers
21 is $VIEW_1 = VIEW_0 \cup \{(B_i, X_i, C_i, Y_i, Z_i) \mid V_i \in G_1\}$.

22 Then, steps 2-k-P and 2-k-V are repeated for $2 \leq k \leq n$.

23 Step 2-k-P: All the verifiers V_i who belong to the group
24 G_k employ the obtained information $VIEW_{k-1}$ to generate a

1 random number $b_i \in \mathbb{Z}_q$, and obtain cryptograms $B_i (= g^{b_i}$
2 $\text{mod } p)$ and $X_i (= A_i^{b_i} \text{mod } p)$. The verifiers V_i then
3 transmit the obtained cryptograms B_i and X_i to the
4 prover P .

5 Step 2-k-V: The prover P examines each i that satisfies
6 $V_i \in G_k$ to determine whether the authentication
7 expression $(X_i = B_i^{a_i} \text{mod } p)$ has been established.
8 If the authentication expression has been established,
9 the prover P transmits the cryptograms C_i , Y_i and Z_i to
10 the verifiers V_i .

11 At this time, the information obtained by the verifiers
12 is $\text{VIEW}_k = \text{VIEW}_{k-1} \cup \{(B_i, X_i, C_i, Y_i, Z_i) \mid V_i \in G_k\}$.

13 As a result, the information finally obtained by the
14 verifiers who are members of the conspiracy is

15 $\text{VIEW}_n = \{(p, q, g, v),$
16 $(A_1, A_2, \dots, A_n),$
17 $(B_1, B_2, \dots, B_n),$
18 $(X_1, X_2, \dots, X_n),$
19 $(C_1, C_2, \dots, C_n),$
20 $(Y_1, Y_2, \dots, Y_n),$
21 $(Z_1, Z_2, \dots, Z_n)\}.$

22 Assumption of calculation amount for conspiracy]
23 In order to establish $x_i = B_i^{a_i} \text{mod } p$ for each i at the
24 step 2-k-V, the verifiers V_i use a random number $b_i \in \mathbb{Z}_q$
25 to calculate $B_i = g^{b_i} \text{mod } p$ and $X_i = A_i^{b_i} \text{mod } p$. In other
26 words, it is presumed that each verifier V_i knows the

1 value of the random number b_i . This assumption can be
2 formally described as follows.

3 b-awareness assumption: hereinafter referred to as BAA]

4 At steps 2-1-V, 2-2-V, ... and 2-n-V, relative to an
5 arbitrary verifier V_i , there is another verifier V_i' who
6 outputs not only the cryptograms B_i and X_i , but also
7 outputs the value of the random number b_i .

8 Configuration of simulator]

9 When the simulator S is constructed as follows, the zero
10 knowledge property can be achieved under the BAA. The
11 simulator S employs the verifiers (V_1' , V_2' , ... and
12 V_n') as sub-routines, and can thus employ the individual
13 random numbers b_i .

14 Algorithm of simulator]

15 Input: public key v , system parameters p , q and g

16 Output: $VIEW_n = \{(p, g, g, v),$
17 $(A_1, A_2, \dots, A_n),$
18 $(B_1, B_2, \dots, B_n),$
19 $(X_1, X_2, \dots, X_n),$
20 $(C_1, C_2, \dots, C_n),$
21 $(Y_1, Y_2, \dots, Y_n),$
22 $(Z_1, Z_2, \dots, Z_n)\}$

23 Step 1: For all "i"s ($1 \leq i \leq n$), random numbers $Y_i \in Z_q$
24 and $Z_i \in Z_q$ are generated, and $A_i = V^{Y_i}g^{Z_i}$ is calculated.

1 At this time, the simulation information produced by the
2 simulator S is
3 $VIEW_0 = [(p, q, g, v), (A_1, A_2, \dots, A_n)]$.
4 Step 2-1-P: The simulator S executes all the verifiers
5 V_i (V_i') who belong to the group G_1 . That is, $VIEW_0$ is
6 input for each verifier V_i' , and (B_i, X_i, b_i) are
7 calculated. At this time, $B_i = g^{b_i} \text{ mod } p$ is established.
8 Step 2-1-V: C_i that satisfies $Y_i = C_i^{b_i} \text{ mod } p$ is
9 calculated. At this time, the simulation information
10 produced by the simulator S is
11 $VIEW_1 = VIEW_0 \cup \{(B_i, X_i, C_i, Y_i, Z_i) \mid V_i \in G_1\}$.
12 Then, steps 2-k-P and 2-k-V are repeated for $2 \leq k \leq n$.
13 Step 2-k-P: The simulator S executes all the verifiers
14 V_i (V_i') who belong to the group G_k . That is, $VIEW_{k-1}$ is
15 input to each verifier V_i' , and (B_i, X_i, b_i) are
16 calculated. At this time, $B_i = g^{b_i} \text{ mod } p$.
17 Step 2-k-V: C_i that satisfies $Y_i = C_i^{b_i} \text{ mod } p$ is
18 calculated. At this time, the information simulated by
19 the simulator S is $VIEW_k = VIEW_{k-1} \cup \{(B_i, X_i, C_i, Y_i,$
20 $Z_i) \mid V_i \in G_k\}$.
21 The communication contents $VIEW_n$, which are finally to be
22 simulated, match the probability distribution of the
23 actual communication contents between the prover P and
24 the verifiers V_1, V_2, \dots and V_n . Therefore, the zero
25 knowledge property is achieved.

1 Advantages of the Invention]
2 As is described above, according to the present
3 invention, the secret key of a prover computer is not
4 compromised by the information exchanged by the prover
5 computer and a verifier computer, and user
6 authentication is ensured.
7 Especially when on an asynchronous network, such as the
8 Internet, a prover computer receives data required for
9 authentication as well as verification from multiple
10 verifiers, the zero knowledge property is acquired.
11 Thus, user authentication is ensured without the secret
12 key of a prover computer being compromised on any kind
13 of network.

14 The present invention can be realized in hardware,
15 software, or a combination of hardware and software. The
16 present invention can be realized in a centralized fashion
17 in one computer system, or in a distributed fashion where
18 different elements are spread across several
19 interconnected computer systems. Any kind of computer
20 system - or other apparatus adapted for carrying out the
21 methods described herein - is suitable. A typical
22 combination of hardware and software could be a general
23 purpose computer system with a computer program that, when
24 being loaded and executed, controls the computer system
25 such that it carries out the methods described herein. The
26 present invention can also be embedded in a computer
27 program product, which comprises all the features enabling
28 the implementation of the methods described herein, and

1 which - when loaded in a computer system - is able to
2 carry out these methods.

3 Computer program means or computer program in the present
4 context mean any expression, in any language, code or
5 notation, of a set of instructions intended to cause a
6 system having an information processing capability to
7 perform a particular function either directly or after
8 conversion to another language, code or notation and/or
9 reproduction in a different material form.

10 It is noted that the foregoing has outlined some of the
11 more pertinent objects and embodiments of the present
12 invention. This invention may be used for many
13 applications. Thus, although the description is made for
14 particular arrangements and methods, the intent and
15 concept of the invention is suitable and applicable to
16 other arrangements and applications. It will be clear to
17 those skilled in the art that other modifications to the
18 disclosed embodiments can be effected without departing
19 from the spirit and scope of the invention. The
20 described embodiments ought to be construed to be merely
21 illustrative of some of the more prominent features and
22 applications of the invention. Other beneficial results
23 can be realized by applying the disclosed invention in a
24 different manner or modifying the invention in ways known
25 to those familiar with the art.